Hot Wires and Fast Molecules:

A Different Look at Pirani Gauges

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This article owes its inspiration to Dr. Bruce Kendall's demonstration of how a simple model aircraft "glow plug" can be used to demonstrate how molecular mean free path plays into the operation of hot wire vacuum gauges, as exemplified by the Pirani gauge. Dr. Kendall's original article was published by the American Vacuum Society in a 1996 monograph [1].

The following will require that the reader have a basic knowledge of how Pirani gauges operate. In brief, the Pirani gauge belongs to the family of indirect reading pressure gauges that depend upon the variation of thermal conductivity of the gas whose pressure is being measured. The specific quantity being measured is the molecule to molecule heat transfer from a heated element to the shell of the gauge tube.

It turns out that thermal conduction is essentially constant in the higher pressure viscous flow regime (i.e. at pressures in excess of a few Torr). This establishes the high pressure measurement limit. It also turns out that gases become very effective thermal insulators in the molecular flow regime i.e. at pressures below about 10^{-3} Torr. However, in the region between these pressures, thermal conductivity will vary with pressure.

Much more detail on Pirani and other thermal conductivity gauges may be found in any standard vacuum text.

Mean Free Path

The mean free path of a molecule is defined as the average distance between collisions of the molecules. At higher pressures the mean free path is shorter because of the higher density. As pressure is reduced the mean free path increases.

A simplified representation is shown in **Figure 1**. If a molecule of diameter d_0 is moving at its thermal velocity through a gas, the distance that the molecule can travel before a collision occurs is related to the diameter of the molecules in the mixture and the number density, *n*, of the gas molecules. The number density is derived from the relationship where Avogadro's number of molecules occupy 22.4 liters at 760 Torr and 273K (0 ºC).

If the incident molecule in the figure is the only one in motion, the mean free path would be:

$$\lambda = \frac{1}{\pi d_0^2 n}$$

However, all of the molecules are in motion so the equation becomes a little more complicated [2]:

$$\lambda = \frac{1}{\sqrt{2}\pi d_0^2 n}$$

In this article we will calculate the diameter of a gas molecule d_0 by using the properties of a simple Pirani gauge to determine the mean free path.

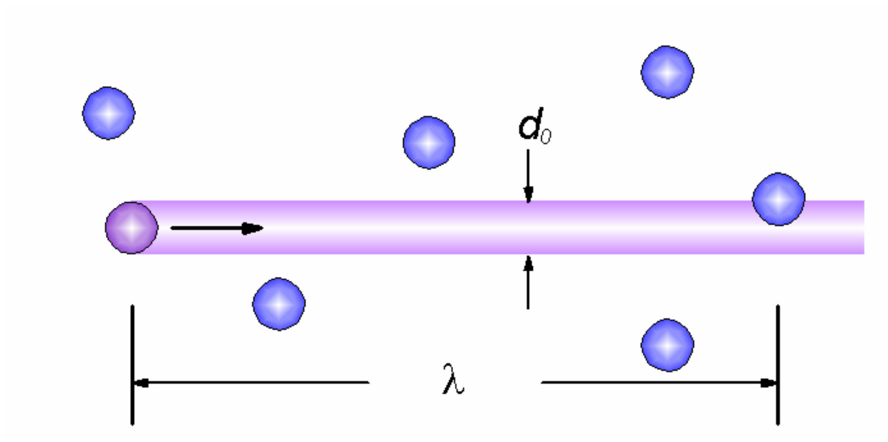

Figure 1. A moving molecule sweeps a path of diameter d_0, eventually colliding with another molecule. This distance between collisions, λ, is the mean free path. In reality, the picture is more complicated because all of the molecules are in motion.

Basis of the Pirani Gauge

A Pirani gauge consists of a heated filament that is housed within a metallic shell. The shell is at ambient temperature and the diameter of the filament is much smaller than the distance from the filament to the shell. At atmospheric pressure we have the situation shown **in Figure 2A.**

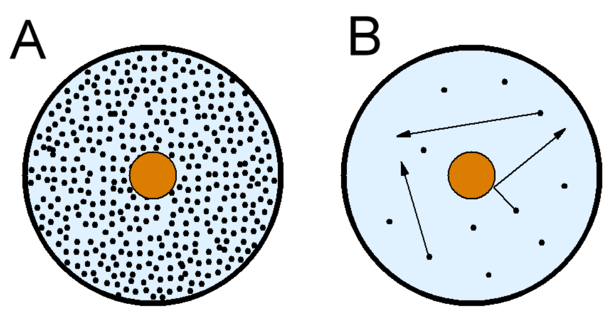

Figure 2. Heated filament within a metallic shell. "A" depicts the situation at higher pressures where the mean free path is short relative to the distance between the filament and the shell. "B" depicts the situation at low pressures where the mean free path is long relative to the dimensions of the shell.

Here the mean free path of the gas molecules is much smaller than the diameter of the filament. As a result, a majority of the gas molecules are impinging on the shell and assume an energy level corresponding to the ambient temperature. Molecules that are heated by the filament will depart the filament with a higher energy but will collide with the cooler molecules and lose energy. Additionally, the vast majority of molecules leaving the filament will also return to the filament after a collision with a cooler molecule because of the short mean free path. The net effect of this is that the filament is transferring much of its thermal energy to ambient temperature molecules and this has a cooling effect on the filament.

As the pressure is decreased, the mean free path will eventually become as long as the filament diameter. In this condition, fewer molecules will collide with the filament. There is a non-linear transition between the first condition (mean free path much less than the filament diameter) and the second where the mean free path is equal to or greater than the filament diameter. This is depicted in **Figure 2B**.

Once the mean free path becomes equal to the diameter of the filament, the relationship between thermal conductivity and pressure becomes linear. At very low pressures (less than about 1 milliTorr) so few molecules collide with the filament that the only heat conduction is via the filament supports and through radiation. Neither of these is a function of pressure.

A Really Simple Pirani Gauge

As Dr. Kendell pointed out, a model engine glow plug can be used to make a very simple Pirani gauge. More importantly, it can be used to show some interesting properties that are related to the operation of a Pirani gauge, specifically the aforementioned relationship between mean free path, d_0, and filament dimensions.

I obtained a plug from an RC model supplier. The preferred type is designed to operate from lead-acid batteries (2 volts) as opposed to dry cell. I measured the diameter as 114 microns. If the reason for measuring the wire diameter isn't apparent now, it will be. The filament is wound as a small coil within the body of the plug. **Figure 3** shows the wired glow plug mounted in a KF16 blank flange.

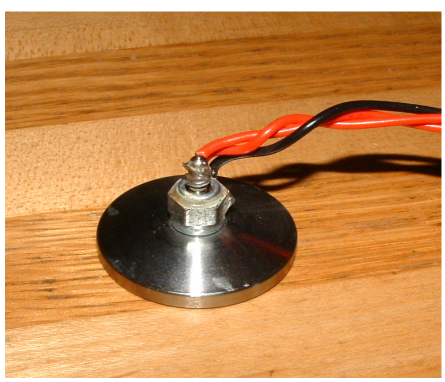

Figure 3. Glow plug with wires and KF16 flange.

As is the case with a commercial Pirani gauge, the filament resistance varies with temperature. The hotter the filament, the higher the resistance. I heated the filament by applying a constant current of 1 amp. A data logger was used to monitor the voltage across the filament as a function of pressure. The flange was connected to a small chamber where the pressure was monitored by means of a commercial Pirani gauge. By slowly varying the pressure in the chamber we can record the voltage across that filament against pressure. **Figure 4** depicts the filament voltage vs. pressure curve.

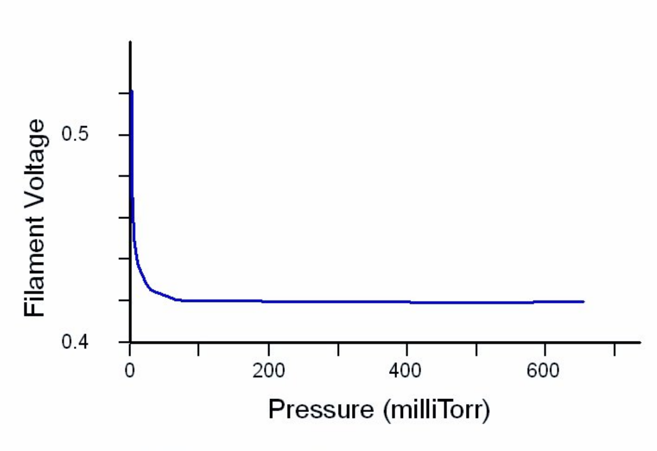

Figure 4. Glow plug filament voltage vs pressure.

The figure shows the flatness of the response above a few 10s of Torr. One important note here – this is essentially a "pure" Pirani gauge in that it does not have a convection mode.

What we really want to see is the trace far to the left where the curve transitions from non-linear to linear. **Figure 5** depicts what we are looking for, specifically the point P_0.

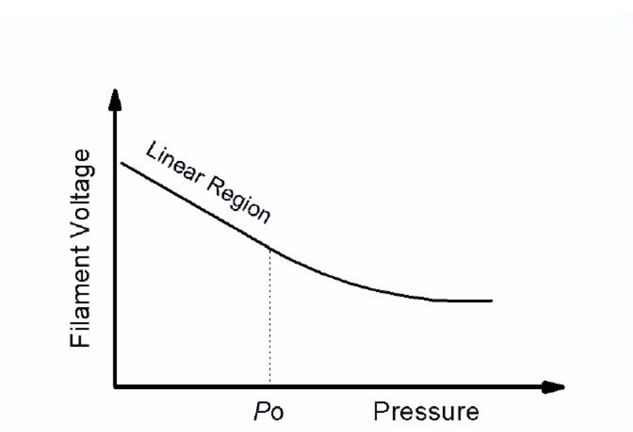

Figure 5. Non-linear to linear transition in the filament voltage vs. pressure curve.

Figure 6 shows the actual curve from the test apparatus in the region of interest.

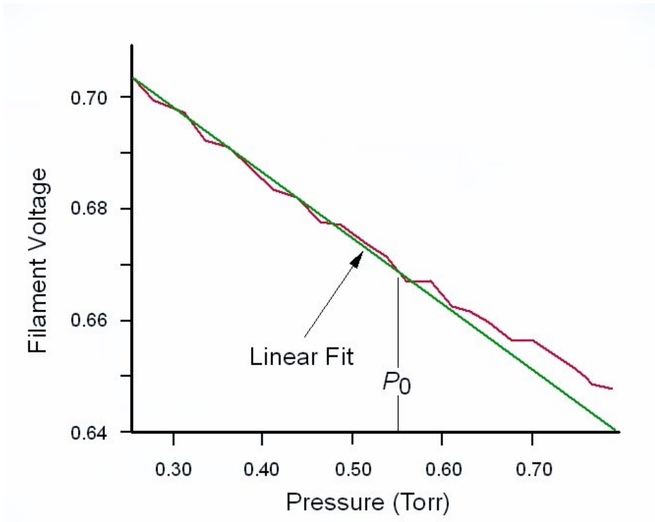

Figure 6. Actual filament voltage vs. pressure curve.

The linear transition occurs at about 0.55 Torr. This is also the point where the mean free path is equal to the diameter of the filament, i.e. 114 microns. This is neat but if we go back to our mean free path equation

$$\lambda = \frac{1}{\sqrt{2}\pi d_0^2 n}$$

we can now solve for the average diameter of the gas molecules within the chamber knowing:

λ = 114 microns (diameter of the filament) or 1.14×10^{-4} m
and
$n = 1.78 \times 10^{22}$ m^{-3} at 0.55 Torr

This gives us a d_0 of 3.3×10^{-10} meters.

If we go to the literature and look up the accepted diameters of nitrogen and oxygen we would find that they are 3.7×10^{-10} meters and 3.6×10^{-10} meters respectively.

It would seem that we are a bit off, but also remember that water vapor comprises a significant fraction of the residual gas in a chamber that started with room air at atmospheric pressure. The literature gives us a value of 2.8×10^{-10} meters for the diameter of a water vapor molecule. So, our measured value may be close after all. As a final point, the value determined by Dr. Kendall with his apparatus also yielded a d_0 of 3.3×10^{-10} meters.

Summary

Hopefully this article was able to provide a little bit of insight into the physics of Pirani gauge operation and why the characteristic curve of this type of gauge looks like it is with regions of linearity with non-linear transitions. We also discovered how we can calculate the average diameter of the residual gas molecules within the chamber by using this curve. Dr. Kendall's demo device has also served as the basis of an educational product [3].

Next time we will look at the very bottom end of the Pirani curve to examine the region where the response flattens out as the residual gas goes into molecular flow.

References

1. Bruce R.F. Kendall in "Educational Outreach at the 42nd National Symposium of the American Vacuum Society," AVS Monograph Series M-16, 1996.

2. John F. O'Hanlon, "A User's Guide to Vacuum Technology, 2nd Edition," John Wiley & Sons, 1989, pp. 11-12.

3. The Science Source, Waldoboro, ME, catalog number 46042, http://www.thesciencesource.com .

Updates July 2019

The Science Source was acquired by another company in 2015 and the product referenced in [3] is no longer commercially available.